Spring 1997

The study of permeability in concrete

Jie Yuan
New Jersey Institute of Technology

ABSTRACT

THE STUDY OF PERMEABILITY IN CONCRETE

by
Jie Yuan

In this study, samples of regular, high performance, expansive and the polymer concrete and mortar were prepared for test of permeability and mechanical property. In the permeability measurement, water and an aqueous chemical solution were employed as the permeant.

The test results of the samples, ranging from 5.7×10^{-9} cm/sec to 1.0×10^{-11} cm/sec for the permeability and 3800 psi to 10600 psi for compression strength, indicated that the polymer coated concrete has the lowest permeability among the concretes and high performance concrete has the highest compression strength . The finding leads to the possibility that a high strength and low permeability concrete material, as required by the environmental container structure, could be achieved through the surface treatment of the high performance concrete with non-permeable polymer. This study also reveals the effects of the size exclusion and the removal of the chemical species up to 97% by the specimen in the case of chemical species used as permeants.

THE STUDY OF PERMEABILITY IN CONCRETE

by

Jie Yuan

A Thesis
Submitted to the Faculty of
New Jersey Institute of Technology
in Partial Fulfillment of the Requirements for the Degree of
Master of Science in Environmental Engineering

Department of Civil and Environmental Engineering

May 1997

APPROVAL PAGE

PERMEABILITY STUDY OF DIFFERENT KINDS OF CONCRETE

Jie Yuan

Dr. George Wei, Thesis Advisor — Date
Associate Professor of Chemical Engineering and Environmental Science, NJIT

Dr. C. T. Thomas Hsu, Co-advisor — Date
Professor of Civil and Environmental Engineering, NJIT

Dr. Mohamed E. Labib, Committee Member — Date
Research Professor of Civil and Environmental Engineering, NJIT

BIOGRAPHIC

Author: Jie Yuan

Degree: Master of Science

Date: May 1997

Undergraduate and Graduate Education:

- Master of Science in Environmental Engineering,
  New Jersey Institute of Technology, Newark, NJ, 1997

- Bachelor of Science in Environmental Engineering,
  Wuhan University of Technology, Wuhan, China, 1992

Major: Environmental Engineering

ACKNOWLEDGMENT

The author wishes to express his sincere gratitude to his advisor, Dr. George Lei, and co-advisor, Dr. C. T. Thomas Hsu, for their guidance, friendship, and moral support throughout this research.

The author is also grateful to Professor Mohamed E. Labib for serving as a member of the thesis advising committee.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

1.1 General

With the ever growing world population and industries, more and more wastes are daily generated. According to the estimate of US Environmental Protection Agency (EPA), there were over 200 million tons of wastes produced in the United States of America in 1992 alone. Mean while, the amounts of hazardous chemical were also manufactured more than ever. Receiving, storing, and handling of these hazardous materials are an integral parts of the whole social activities. Until now, for solid and liquid hazardous materials, the most practical and economical method to deal with them is storing in containers, which were so called environmental containment structures. However, in these structures, leaching is a big problem. Among the several millions of underground storage tanks in USA, nearly 25 percent are now leaking. The toxic are polluting our soil and groundwater. Construction of the environmental containment structures to prevent any accidental release of these hazardous materials into the environment present a formidable challenge to environmental engineers. With such a view in mind, this thesis is aimed to development a new concrete material that would confine the hazardous wastes in storage without leakage.

1.2. Concrete and Permeability

Concrete, as a traditional building material, is widely used for constructing industries buildings, highways, bridges, as well as residential homes. In generally, the material must posses a high strength to support the load. However, for the environmental containment structures, the concrete must also have the property of preventing the toxic wastes to leak through the structure. To be more specific, it must have a low or none permeability of gases or liquid. In order to develop such a material, a fully understanding of the micro structure of the concrete is necessary.

Since the pore system is the main path for liquid in concrete, let us first examine the pore structure in the concrete. Pores in the normal-weight concrete are considered a part of the paste fraction covering a wide range of sizes as classified by Powers and IUPAC in the following table:

Table 1. Pore size classifications for cement paste

Powder Classification

Gel	Capillary	Air Voids

2.5 10 50 10,000 Pore Diameter (nm)

IUPAC Classification

Micro	Meso	Mscro	Air Voids

The traditional classification suggested by Powers and Brownyard [1] are only two classes: the gel pore and the capillary pore. The gel pores are associated with the formation of the hydration products ,cement gel, which is considered as the intrinsic porosity, while the capillary pores are considered as the remnants of the water-filled spaces. The other classification is based on the behaviors of the water in the pore. The intrinsic porosity consists of micropores and the smaller mesopores. The capillary pore system is made of meso and macropores. Since the diameter of the capillary pores are in the range of 10 nm to 10,000 nm, if they form a continuous system, they would provide an easy path for liquid to flow. In fact, the flow of liquid in concrete involves in mostly the capillary pores. In order to have a low permeability of the concrete, the fraction of the capillary pores must be minimized.

Another path for the liquid flow is through cracks. During the curing period of the concrete, the material shrinks and creates cracks. If the cracks connect to one another or connect to the capillary pores to form a continuous system, that would provide path for liquid to leak. The capillary pores are also formed during the curing period as a result of the evaporation of remaining water which has not reacted with the cement.

The following approaches are applicable to eliminate or minimize pores and cracks in the concrete:

1. reduce the water/cement ratio , and let the water react fully with the cement, so that no extra water is left for evaporation.

2. apply ultra-fine fillers to avoid pores and cracks.

3. use expandable cement to fill up the pores and cracks

4. avoid water evaporation during the curing period of the concrete.

Based on these considerations, samples of high the performance , polymer and the expansive concrete as well as the regular concrete will be prepared for the research.

1.3 Property of Materials

1.3.1 High Performance Concrete

The high performance concrete has been developed and known for its high strength and high modules of elasticity for quite some time. It contains a silica fume and the regular concrete components sand, cement, and aggregates. Samples of this concrete will be prepared for this research at a reduced water-cement ratio. So that the voids of the concrete could be reduced to a minimum by less water evaporation and reduction of the pores by ultra-fine silica fume.

1.3.2 Polymer Concrete

Polymer Concrete is also known as Polymer Modified Concrete, it is defined as a kind of composite material by physically combining two or more existing materials to produce a multiphase with different physical properties from the original materials. The constituents retain their identity. Thus the polymer concrete has the properties of both polymer and the concrete. In generally, it has high strength in tension, compression and bending.

1.3.3 Expansive Concrete

The expansive cement has an unique property to expand its volume during the period of hydration. The expanded volume would probably be sufficient to make up the shrinkage of the concrete during its drying period, and hence reduces the capillary pores. The expansive concrete is also know as shrinkage-compensating concrete.

1.4 Development of Equation to Calculate the Permeability

1.4.1 Introduction

Permeability is the property of a material that represents the ease with which water or other fluids can move through it. Permeability coefficient **k** is defined as the capacity of a porous medium to transmit fluid. It is expressed in velocity units centimeter per second. The permeability coefficient is a material constant independent of the fluid used, it can be described by Darcy's law for laminar flow through the porous medium:

$$dq/dt = KA(\Delta H/L) \qquad (1)$$

where dq/dt is the rate of flow, A is the cross-sectional area of the specimen, and $\Delta H/L$ is the hydraulic gradient across the section. K is the permeability coefficient. It is a property of materials, can be effected by the composition , structure and making process of the material. The permeability coefficient can be determined by two different experimental methods, constant head or falling head method. In this research, the falling head method has been employed .

1.4.2 Equations for Failing Head Test

According to the Brainard-Kilman pressure and volume control system, discharge Q and the total hydraulic head H_1 and H_2 are measured, as shown in Fig.1 schematic diagram ,

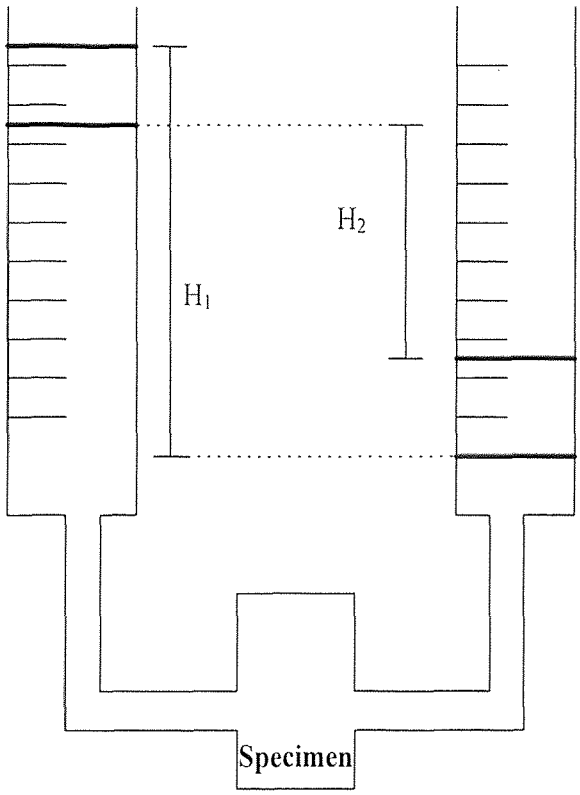

Figure 1 The schematic diagram of falling head permeability test apparatus

The permeant, water, flows from one standpipe through the specimen into the other standpipe. The rate of discharge, Q, is calculated by the increase in the water level at the outflow standpipe. However, for this system, the panel readings on the standpipes

are the height of the two water levels. Therefore, to obtain the volume levels of the two standpipes, the reading should be multiplied by a factor. The factor is the equipment constant. The inlet, outlet, and cell pressure are obtained directly from the digital gages. If the first reading is taken at the time , t = 0, the elevation difference between two standpipes is noted as H_1 in cm, and the second reading is taken at time the t = t , then the elevation difference is noted as H_2 in cm. The pressure in psi applied on inlet, Pi, and outlet, Po are constants. Then the total hydraulic difference, h (cm), is defined as below:

$$h = H + \frac{(P_i - P_o)psi \times (12in/ft)^3 \times 2.54cm/in}{62.4lb/ft^3} \qquad (2)$$

where H is hydraulic head in cm.

The Darcy's law can be used in this case. It may be expressed as:

$$V_{df} = ki \qquad (3)$$

where V_{df} is the Darcy flux velocity (specific discharge). i is the hydraulic gradient, and k is know as permeability coefficient.

The hydraulic gradient, i, is defined as the hydraulic head difference, h (cm), divided by the distance, L (cm), along the flow path where the head difference occurs.

$$i = \frac{h}{L} \qquad (4)$$

The flow rate, Q, through the specimen is equal to the flow velocity times the cross-sectional area, A in cm^2, i.e.

$$Q = V_{df} xA \tag{5}$$

Substituting the equivalent value of V_{df} from equation (3), results in equation (6):

$$Q = k\frac{h}{L}A \tag{6}$$

On the other hand, the flow rate can also be expressed as the rate of changes of the water levels in the standpipes:

$$Q = -\frac{1}{2}a\frac{dh}{dt} \tag{7}$$

where, a in cm^2, is the cross-sectional area of the standpipe. dh is the change of the difference of the hydraulic head during the time interval dt.

Combining equations (6) and (7), one obtains:

$$dt = \frac{-aL}{2kA}\left(\frac{dh}{h}\right) \tag{8}$$

Integrate the above equation between the time interval from zero to t; and the corresponding total hydraulic head from h_1 *to* h_2, then we get:

$$\int_0 dt = \frac{-aL}{2kA}\int_{h_1}^{h_2}\left(\frac{1}{h}\right)dh \tag{9}$$

and results in equation (10):

$$t = \frac{-aL}{2kA}\ln\left(\frac{h_2}{h_1}\right) \tag{10}$$

or equation (11),

$$t = \frac{aL}{2kA}\ln\left(\frac{h_1}{h_2}\right) \tag{11}$$

Rearrange the above equation, so that ***k*** can be calculated through equation (12):

$$k = \frac{aL}{2tA} \ln\left(\frac{h_1}{h_2}\right) \tag{12}$$

where:

$$h_1 = H_1 + \frac{(P_{i1} - P_{o1}) \times 12^3 \times 2.54}{62.4} \tag{13}$$

$$h_2 = H_2 + \frac{(P_{i2} - P_{o2}) \times 12^3 \times 2.54}{62.4} \tag{14}$$

where Pi_1 (psi) is the pressure applied to the inlet at time zero and Po_1 (psi) is the pressure applied to the outlet side at the same time. Pi_2(psi) and Po_2(psi) each shows the pressure applied to the inlet side and the outlet side at the time t. Because the pressure did not change with time, therefore $P_{i1} = P_{i2} = Pi$ and $P_{o1}=Po_2=Po$ for equation (12)-(14). The unit for the pressure is pound per inch (psi) and for h is centimeters (cm), therefore, the calculated permeability coefficient, ***k***, is in units of cm/sec.

CHAPTER 2

EXPERIMENTAL

2.1 Material and Specimens Preparation

2.1.1 Materials

In this research, the following materials were used to prepare the samples.

Portland Cement: Type I and Type K, Supplied by Blue Circle Cement Company, NJ

Sand: finess 2.8, from local source.

Basalt: maximum size 3/8 inch, from local source.

Silica fume: from Elkem Chemicals, Inc.

Superplasticzer: from Master Builders, Inc.

Tap water

2.1.2 Preparation of High Performance Concrete

The high performance concrete and mortar were prepared by mixing Type I Portland cement (ASTM 150 standard), sand, basalt, tap water, silica fume and superplasticizers. The weight percentages of each component are listed in Table 2 and 3. The sample of the high performance mortar was prepared for the purpose of comparison.

Table 2. Composition of high performance concrete

Component	weight %	Weight for 500 in^3 concrete (lb)
Portland cement	27	11.67
water	8	3.42
sand	18	7.53
stone	44	18.99
silica fume	3	1.30
superplasticizer		0.18 l

Table 3. Composition of high performance mortar

Component	weight %	Weight for 500 in^3 concrete (lb)
Portland cement	27	11.67
water	8	3.42
sand	62	26.52
silica fume	3	1.30
superplasticizer		0.18 l

2.1.3 Preparation of Polymer Concrete

The polymer concrete was made by adding a few percent of the polyacrylic emulsion to the premixture of the cement paste and the aggregates. The water/cement ratio was 0.54(the ACI recommend ratio for the regular 4000 psi concrete). The water in the polymer emulation was taken into account in the calculation of the water needed for the w/c ratio. The weight present of each component in the polymer concrete is listed in Table 4.

Table 4. Composition of the polymer concrete

Component	Proportion (weight %)	Weight for 0.3 ft^3 concrete (lb)
cement	19.5	8.8
water	7	3.21
sand	27.5	12.4
stone	43	19.2
Polymer	3	1.40

2.1.4 Expansive Concrete

The expansive concrete was developed in the 1970s. There are three types of expansive cements, but only one, Type K, is commercially available in the United States. The composition and weight % of the concrete are listed in Table 5.

Table 5. Composition of expensive concrete

Component	weight %	Weight for 500 in^3 concrete (lb)
cement	14	6.5
water	7	3.3
sand	35	16.69
stone	44	21.43

2.1.5 Preparation of Regular Concrete

A regular concrete (4000 psi concrete) and a mortar were also prepared as the control for comparison,. Their compositions were based on the standard practice of ACI 211.1-89 and are listed in Table 6 and Table 7.

Table 6. Composition of regular concrete

Component	Proportion (weight %)	Weight for 500 in^3 concrete (lb)
cement	14	4.5
water	7	2.27
sand	35	11.5
stone	44	14.8

Table 7. Composition of regular mortar

Component	Proportion (weight %)	Weight for 500 in^3 concrete (lb)
cement	14	4.94
water	7	2.82
chamber sand	79	21.2

2.1.6 Concrete Coated with Polymer

A 15% polyurethane solution was applied to the surface of a regular concrete. Coating were repeated for several times to make sure all the voids on the surface of the concrete were covered.

2.1.7 Preparation of Specimen

Out of each concrete or mortar sample, nine specimens were prepared, three 3 × 6 inch specimens for mechanical tests , three 4 × 2 inch and three 4 × 1 inch for permeation

tests. All of these specimens were prepared under the same conditions for material mixing , casting and curing.

All mixing were done in a rotary mixer. Initially, the coarse and/or fine aggregates were loaded for dry mixing for 2 to 3 minutes. And then, the cement and/or silica fume were added to mix for another 1 to 2 minutes. Finally, the water and superplasticizers or polymer were added to the cementitious material and continued to mix for at least 5 minutes until a moldable homogeneous mass was achieved. The resulting mixture was then transferred to the cylindrical molds which were prelubricated with oil.

During the casting, a table vibrator and a steel bar were employed to facilitate the compact of the homogeneous mass in the mold. All the specimens were covered with plastic film immediately after the casting , and were left at the room temperature for 24 hours to cure . The demold specimens were further cured in a lime saturated water for 28 days and dried at room temperature for several days before test.

2.2 Test

2.2.1 Strength

The 3 × 6 inch specimens were used for the strength test. Before test, both ends of the specimen were capped with sulfur to eliminate possible end effect. While the specimen was fastened on the testing machine, a preload was applied followed by an increasing load at a rate of 1000 lb/min., until the specimen failed. The maximum breaking load was recorded .

2.2.2 Permeability

Preparation of Specimen

The Darcy's law is based on the assumption that the medium was saturated with the liquid. Hence, the permeability of a fine porous material should be determined only under saturated conditions. In this experiment, a back pressure of 40 psi was applied. Under this pressure, it was reasonably to assume that the specimen was 100% saturated with the liquid vapor. However, in order to shorten the saturation time, the specimens were stored in the distilled water at room temperature before the test.

Equipment Setup

The test equipment consists of two parts: several chamber cells and a control panel. The schematic diagrams of the equipment are shown in Figs 2 and 3. In each test, three chamber cells were used for each sample of concrete or mortar. The specimen was placed in the cell which was then filled with water. The cell was connected to the control panel with hard hoses that could stand the water pressure. The system was checked for leakage before each test. The procedure of setting up the equipment is briefly described as the following:

Chamber Cell

1.Place the porous stone on the top of the base plate.

2.Place the specimen on the top of the porous stone.

3.Place another porous stone on the top of the specimen and then place the upper cap on the top of the porous stone.

4. Check the rubber membrane for leakage by placing air blown membrane inside a water bath.

5.Place the rubber membrane over the specimen, the cap, and the base plate. Make sure that the membrane completely covers both the cap and base plate.

6.Place 0-ring to the base plate and to the upper cap.

7.Position the cylinder of the Permeameter cell around the specimen.

8.Place the top plate on the cylinder and fasten the Permeameter by tie rods.

Control Panel

1.In order to fill the chamber cell with the desired amount of water, the bottom plate is connected to position B in Fig. 3 via a plastic tubing. The chamber pressure is released by means of a hose connected to the top plate. Turn the switch A to "Fill."

2.After the chamber is filled with water, transfer the tubing from position B to position 0. Remove the hose from the top plate.

3.Connect position P to the water inlet and position Q to the water outlet on the cell..

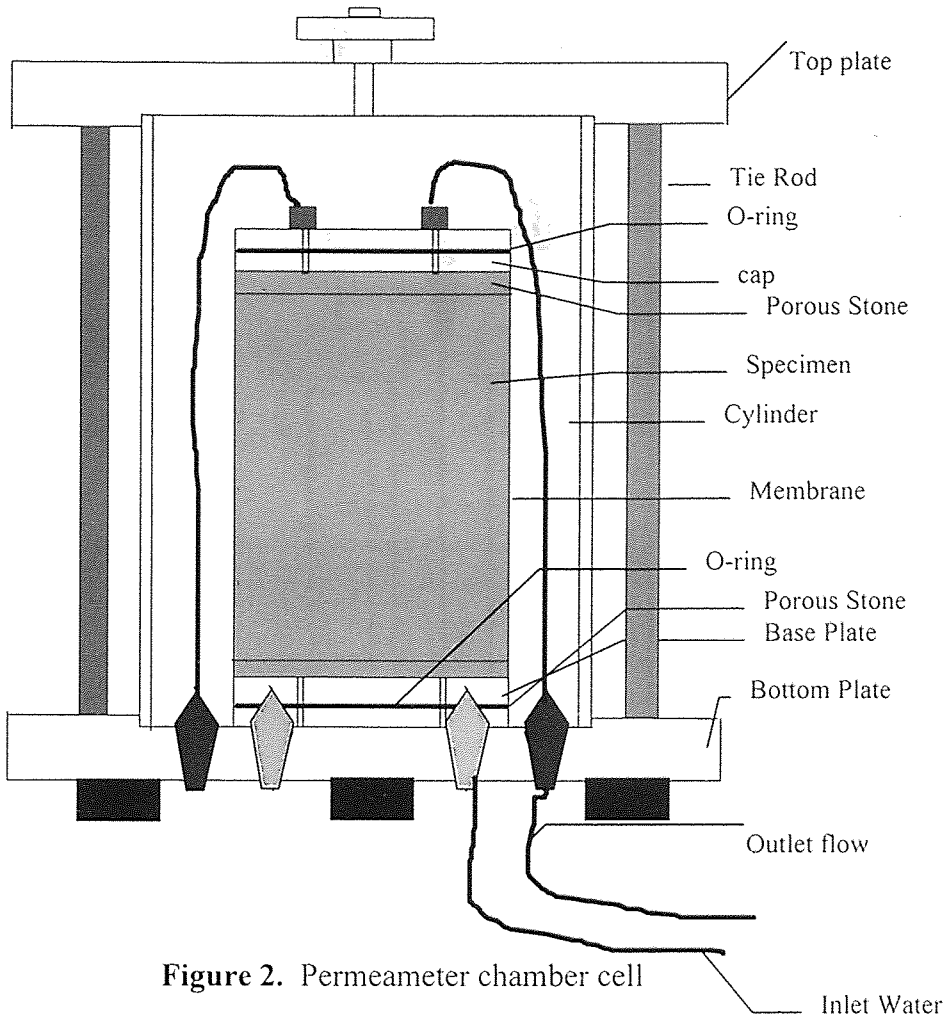

Figure 2. Permeameter chamber cell

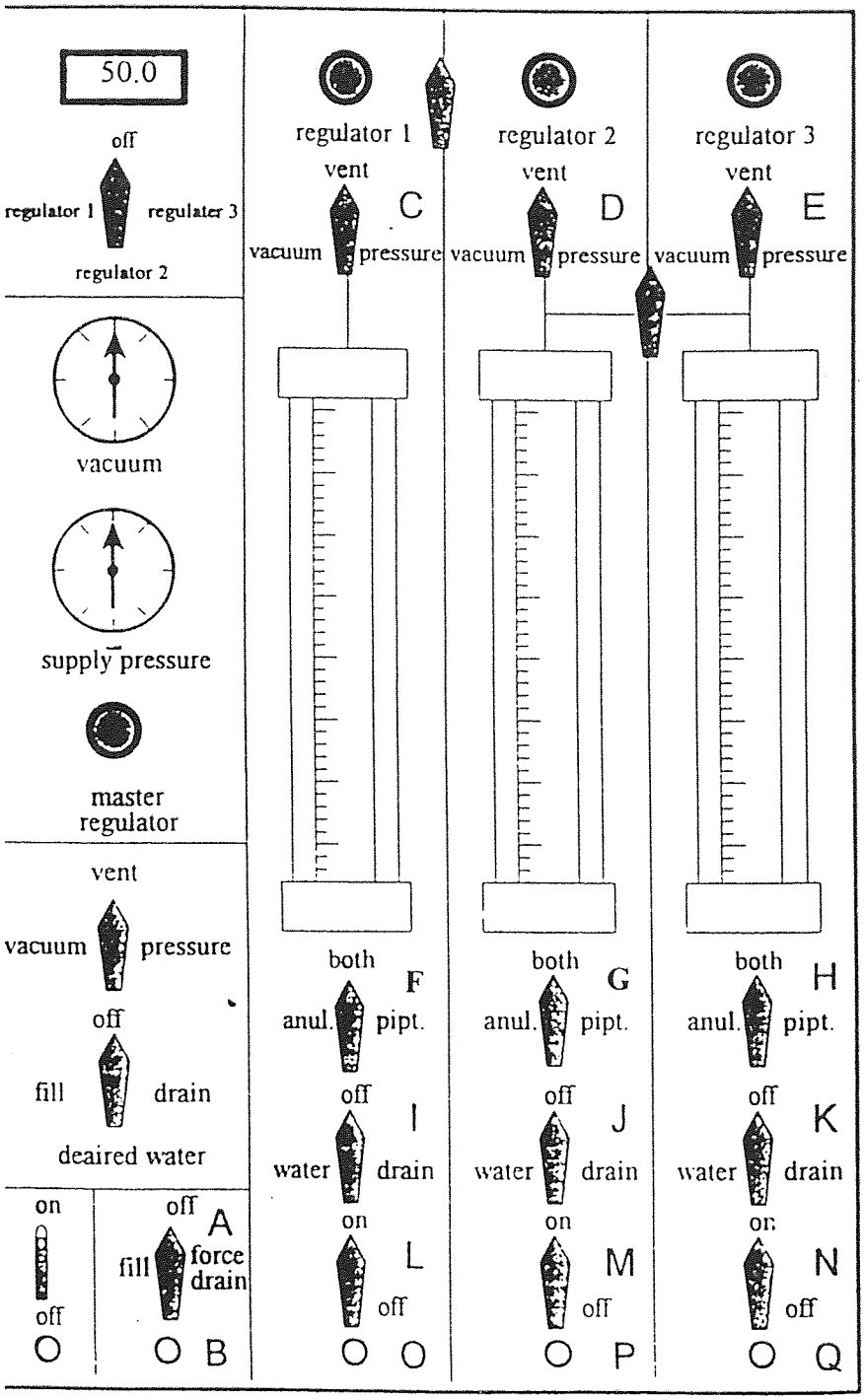

Figure 3. Brainard-Kilman control panel

Permeability Test

The permeability of the specimen was calculated from the measurement of the water volume transmitted through the specimen. The transmitted water could be easily measured by means of the apparatus shown in figures 2 and 3. Through the knobs on the control panel the inlet and outlet pressures could be adjusted separately. So that the water level on the standpipes in the control panel could be read out. The water pressures on the standpipes were supplied by an air compressor. The outside water pressure of the rubber membrane was set high enough to avoid any leakage from the interior of the membrane.

For pressure settings, regulators 1, 2, and 3 were used to adjust the pressures at cell, inlet, and outlet. In this experiment, the cell pressure was set at 50 psi (344 kPa), inlet pressure 40 psi (275 kPa), and outlet pressure 10 psi (69 kPa). The reason for the higher cell pressure over the inlet water pressure was to prevent leakage from the outer surface of the cell; and to keep the specimen in an environment of 100% saturation in humidity at all times.

The standing air was removed from all the tubing through vents. And the water levels were set in each standpipe to achieve highest at the inlet and lowest at the outlet.

During the test, the switch F was turned to "pipette" and switch G & H was turned to "annulus". Valves L, M, and N were turned on to let water flow through the specimen. The volume changes in the three standpipes were recorded. The pressures on the inlet and the outlet standpipes were adjusted to accelerate the velocity of the water flow through the specimen. The water levels in the three standpipes were reset regularly each time the reading was taken.

The time, the temperature of the water, the pressure (psi) at the outlet, and the inlet flow, and the water levels in each standpipe were recorded three times a day during the entire course of the test.

Whenever the in-flow became equal to the out-flow, a constant flow at the downstream was established (show no further reduction in flow rate), and the test was stopped. In this way, a total of thirty-six specimens were tested.

Data Calculation

The permeability coefficient, k, for each specimen was calculated through equation 12

$$k = \frac{aL}{2tA} \ln\left(\frac{h_1}{h_2}\right) \qquad (12)$$

Where a (cm^2)is the cross-sectional area of the standpipe; L (cm) is the average height of the specimen; A (cm^2) is the cross-sectional area of the specimens; t (sec) is the time interval between the two consecutive readings; h_1 and h_2 (cm) are the hydraulic heads, including the pressure head and the water elevation head during the time period.

2.2.3 Chemical Removal

An aqueous solution, consisting of 1000 PPM each of Cr^{6+} and Pb^{2+}, and dichorofluorescein plus 2000 PPM phenol, was prepared. For this experiment, the equipment had to be modified slightly to suit the experiment. Two small cylindrical containers were used for the inflow and the outflow solutions. The pressure applied was

the same as that of the permeant, pure water. The schematic diagram of the modified equipment is shown in figure 4.

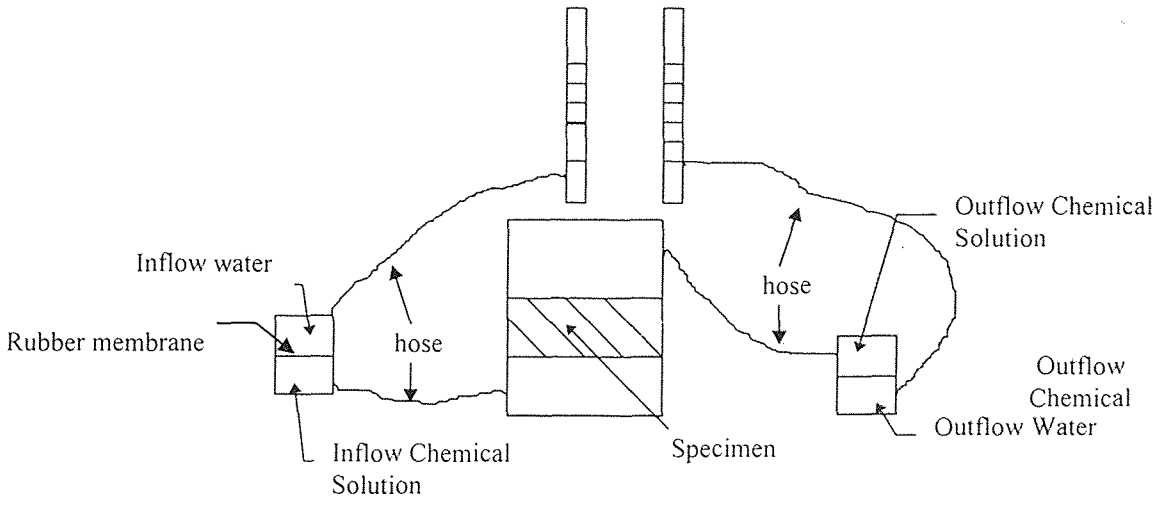

Figure 4. Schematic diagram of the modified test equipment for chemical solution

The experiment of permeating the chemical solution lasted more than four weeks, at the end of the 30th day, the chemical solutions in the inflow and the outflow containers were analyzed by the flame atomic absorption (FLAA) for the heavy metals ions and by the high performance liquid chromatography (HPLC) for the organic chemicals..

The principle of AA spectrometry is based on the fact that neutral or ground state atoms of an element can absorb electromagnetic radiation over a aeries of very narrow, sharply defined wavelengths. The sample, in solution, is aspirated as a fine mist in a flame where it is converted to an atomic vapor. Most of the atoms remain in the ground state and are therefore capable of absorption radiation of a suitable wavelength. This

discrete radiation is usually supplied by a hollow cathode lamp, which is a sharp line source consisting of a cathode containing the element to be determined along with a tungsten anode. When a sufficient voltage is impressed across the electrodes, the filler gas is ionized and the ions are accelerated towards the cathode. As these ions bombard the cathode, they cause the cathode material to sputter and form an atomic vapor in which atoms exist in an excited electronic state. In returning to the ground state, the lines characteristic of the element are emitted and pass through the flame where they may be absorbed by the atomic vapor. Since, generally, only the test element can absorb this radiation, the method becomes very specific as well as sensitive.

HPLC is a very important instrument for organic analysis. It separates components in a mixture based upon their relativity affinity for partitioning between different phases. Two different phases are generally used in modern chromatography to effect separation of a mixture, one is the stationary phase and the other the moving phase. The stationary phase may be either a liquid or a solid, the mobile phase is liquid. The sample is injected to the system and pushed through the analytical column by the solvent, separation of the components occurs. A suitable detector for the species of interest is used at the column exit, and the response is stored, integrated, and recorded. Waste solvent is collected for safe disposal.

The solvent, column packing, and the detector are selected based upon the suitability for the compound of interest and the sensitivity of the detection required. In the experiment, water was selected as the solvent and the X-ray Fluorescencor as the detector.

CHAPTER 3

RESULT AND DISCUSSION

3.1 Strength of Materials

Three specimens were tested for each material. The results reported in Table 8 are the average value of each three tests. Variations in each three tests are no more than 10%.

Table 8. The compression strength of the materials

Material	28 day Compression Strength (psi)
Regular Concrete	4200
High Performance Concrete	10600
Polymer Concrete	3800
Expansive Concrete	4200

An examination of these results appear to be normal.. The strengths of the regular and the expansive concretes are slightly higher than that of the normally reported value, 4000 psi for these materials. This may be contributed by the better mixing and curing of these samples in our preparation. The strength of the polymer concrete is slightly lower than the expected value, only 3,800 psi. However, the average strength of high performance concrete has reached to 10,600 psi. It is 2.7 times higher than that of the regular concrete.

3.2 Permeability of the Materials

3.2.1 Permeability of the Regular Concrete

The permeabilities of the regular concrete and the mortar as a function of time are shown in figure 5. The constant values, 5.7×10^{-9} cm/sec and 4.5×10^{-10} cm/sec separately for the concrete and mortar, are established after 120 hours. Based on the permeability of the regular concrete, the liquid can leach out a 2.5 inch thick concrete structure in about 35 years.

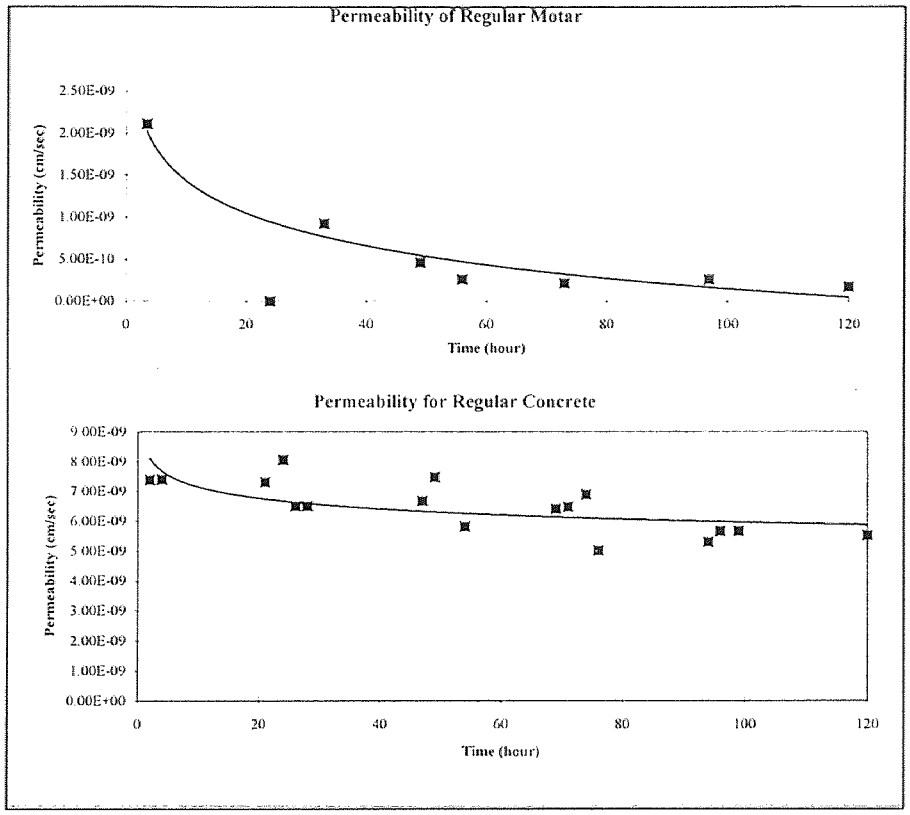

Figure 5. Permeability of regular concrete and mortar

3.2.2 Permeability of High Performance Concrete

The permeability of high performance concrete and mortar are shown in Fig 6, separately about 2.3×10^{-10} cm/sec and 1.0×10^{-11} cm/sec. Compare the former with the permeability of the regular concrete, 5.7×10^{-9} cm/sec, results in a ratio, 1 to 25.

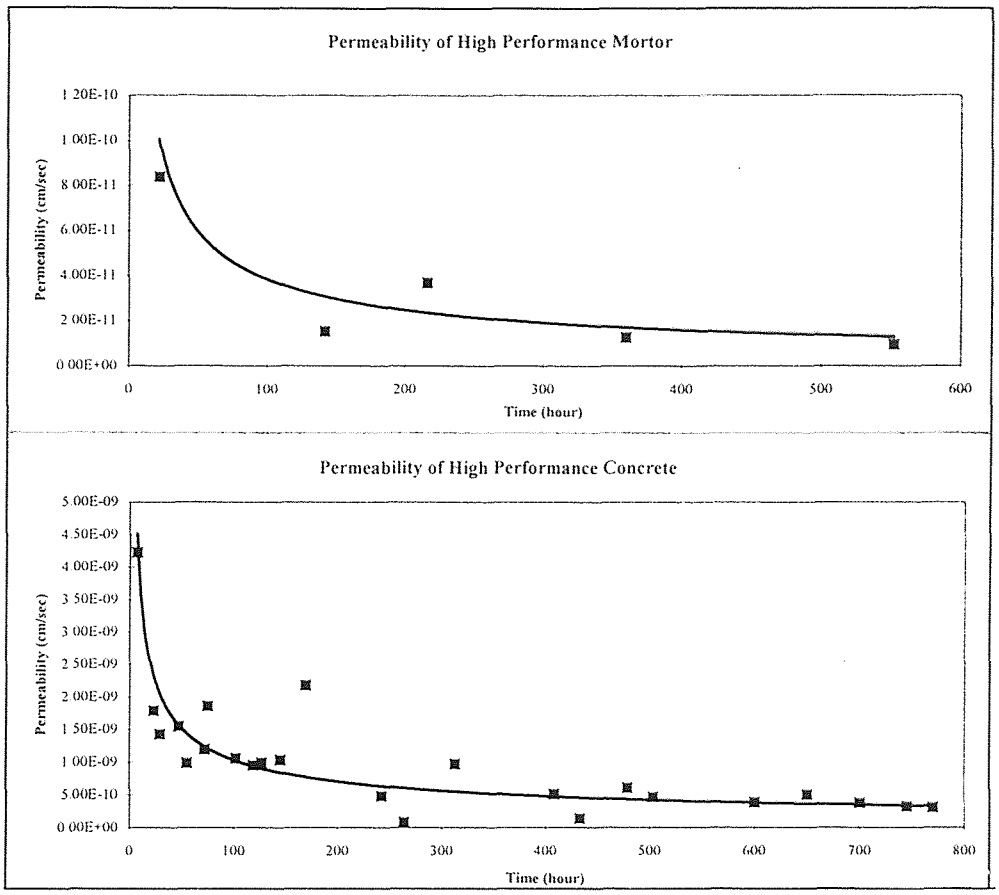

Figure 6. Permeability of high performance concrete and mortar

Reasons for the low in permeability of the high performance concrete are twofold. One is its composition change with the use of silica fume, the other is the reduction of the water to cement ratio to 0.29 (0.57 is normally used for the regular 4000 psi concrete). As mentioned in the Introduction , the capillary pores of the concrete are usually formed as a

result of the water evaporation. The smaller water to cement ratio limits the water only to form hydrate with cement, and no excess left for evaporation. So that the capillary pores are reduced. The silica fume in the high performance concrete not only increases the workability but also reinforces the strength of the concrete. The silica fume is a by-product from the reduction of high purity coal in electric arc furnaces or from the production of silicon and ferro-silicon alloys. It has a high content of amorphous silicon dioxide of very fine spherical particle size, which is about 100 times smaller than a grain of ordinary Portland cement. Because of the content of silicon dioxide (SiO_2) and the fine particle size, silica fume is extremely reactive with the Portland cement. The silica fume acts in the concrete not only as a strength reinforcer but also as a filler for the pores to reduce voids. As a result, the permeability of the material decreases. Other factors such as the use of the uniform and clean aggregates, quick mixing, and better curing are all contributing to the high strength and low permeability of the concrete.

3.2.3 Permeability of Expansive Concrete

As shown in Figure 7, the permeabilities of the expansive concrete and mortar are separately 7.7×10^{-11} and 5.0×10^{-11} cm/sec. To compare the former with that of the regular concrete, the permeability of the expansive concrete is about 80 times less. When the expansive concrete is in the stage of moisture curing, the necessary restraint(here the mold) must be provide to prevent it from curling. Failure to do so will result in an unrestrained expansion that would in turn cause cracking in the air drying and curing period.

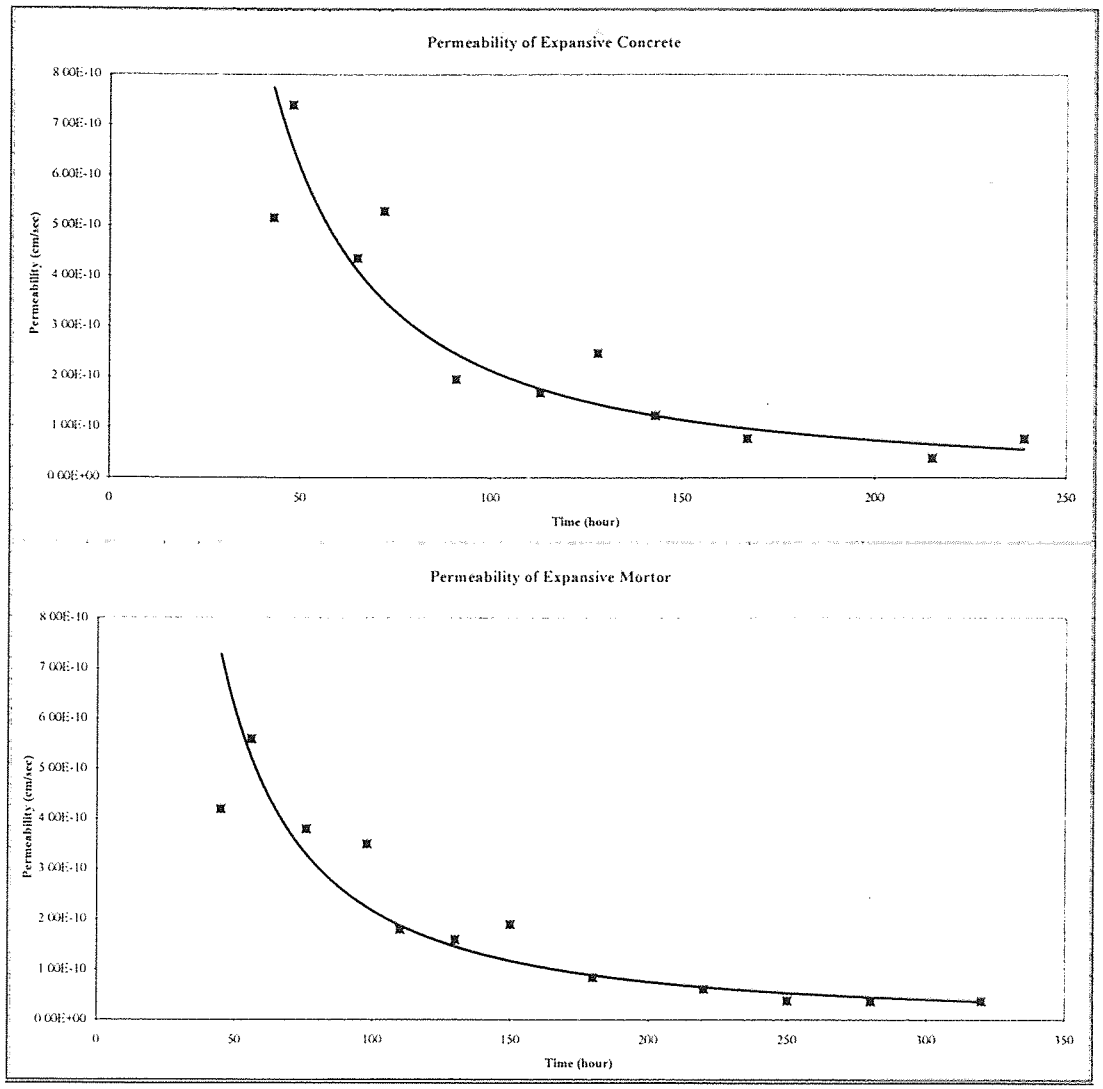

Figure 7. The Permeabilities of the expansive concrete and mortar

As shown in Figure 8, during the moisture curing period (4 - 7 days), the expansive concrete expands while the regular concrete shrinks slightly. But in the normal air during curing period, the shrinkage of the expansive concrete is compensated by its early expansion, while the regular concrete continues to shrink until being fully cured.

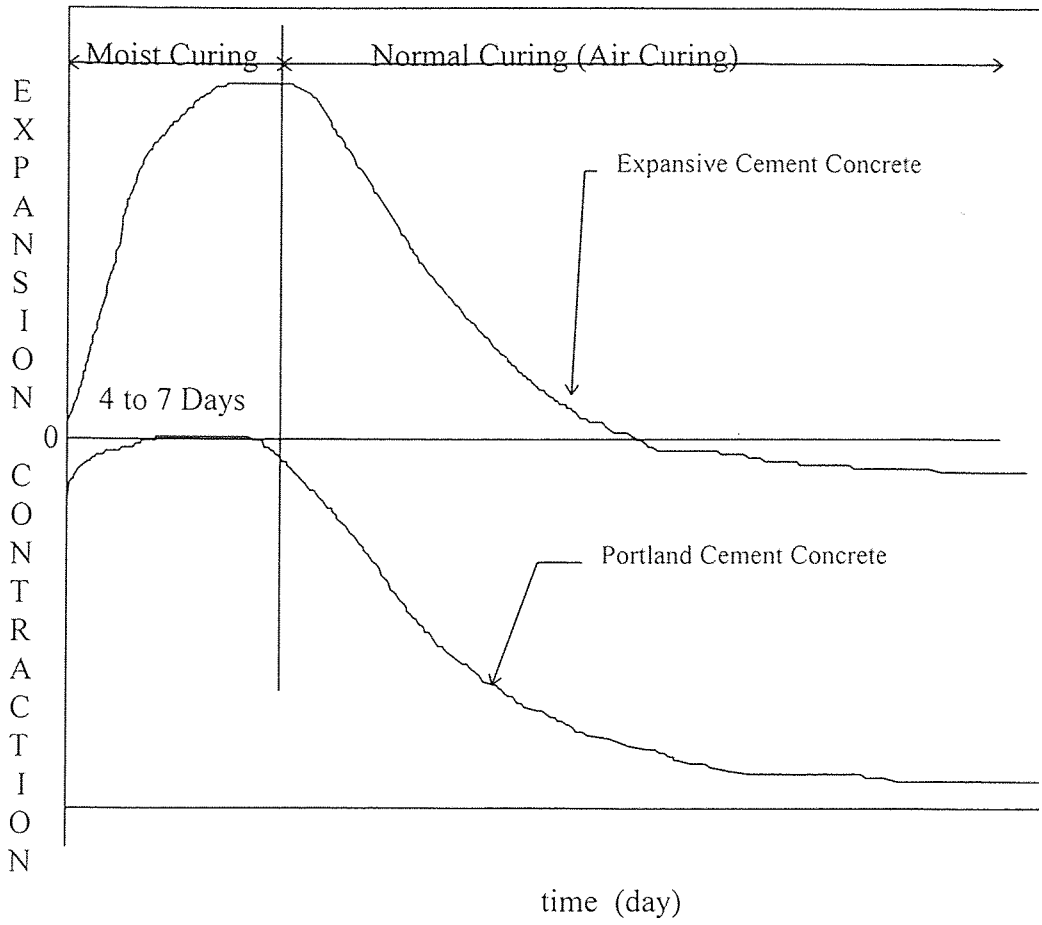

Figure 8. Concrete expansion and shrinkage

The expansion of the expansive concrete makes it possible to have a monolithic structure, that would eliminate the potential leaky ways of the contraction joints. With the advantage of low permeability, the expansive concrete could be considered as a good material for environmental container structure.

3.2.4 Permeability of Polymer Concrete

1). Polymer - Cement Blend

In this blend, a slightly tacky acrylic polymer emulsion was used to replace part of the water which is used in the mixing of the sample. The polymer molecules were thought to adhere the cement particles that would form a less porous material. Figure 9 indicates that after 200 hours, the permeability of the sample reaches a constant value at about 5.3×10^{-10} cm/sec. Compare it with that of the regular concrete, 5.7×10^{-9} cm/sec, it is about 10 times less, but compare with that of the expansive concrete, 7.7×10^{-11} cm/sec, and the high performance concrete, 2.3×10^{-10} cm/sec, it is about 7 and 2 times higher.

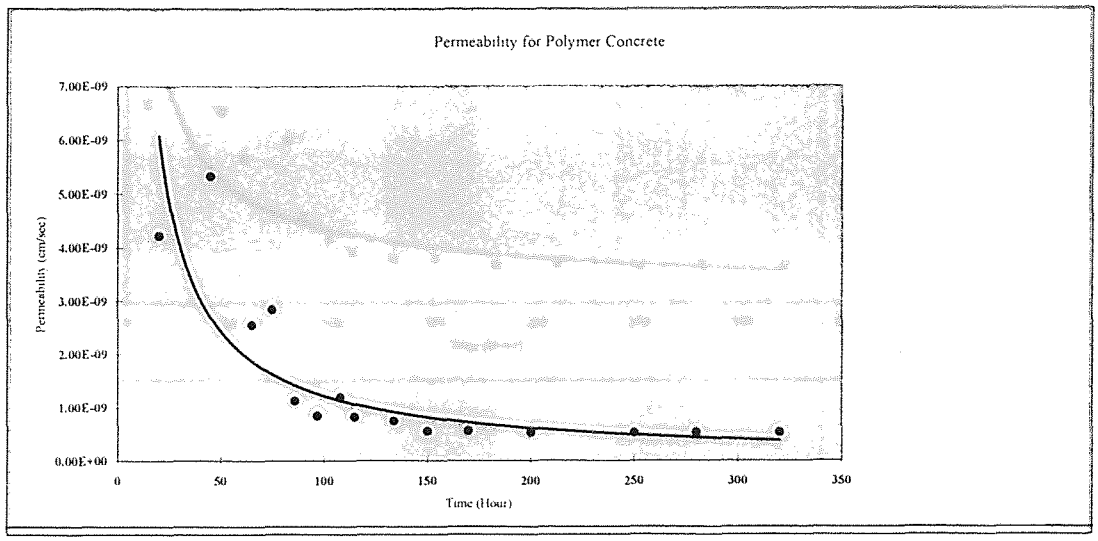

Figure 9. Permeability of polymer concrete blend

2) Concrete coated with polymer

The regular concrete specimen was coated with a thin layer of polyurethane. The permeability of this sample is shown in Fig. 10, about 5×10^{-11} cm/sec. Compare this value with other samples, it is about 115 times lower than 5.7×10^{-9} cm/sec for the

regular concrete and about 4.5 times lower than 2.3 × 10^{-10} cm/sec for the high performance concrete. Therefore, coating of the concrete may provide an alternative method to reduce the permeability of the existing environmental container structure. However, the resistance of the polymer to chemicals must be carefully considered.

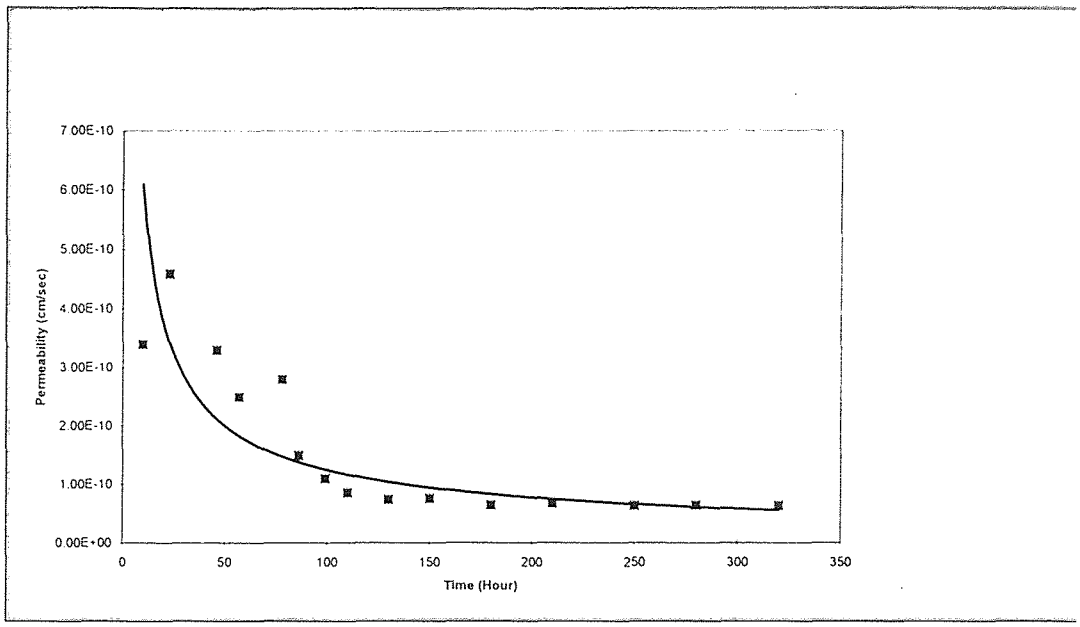

Figure 10. Permeability of polymer coated concrete

3.3 Comparisons of Permeability of Concrete and Mortar

Comparisons of permeabilities of concretes and mortars for the samples are shown in Figure 11. It is well known that the cement-aggregate interface is more porous than that of the bulk paste. Our results shown in figure 11 reaffirm this point. As one may note that all the mortars have the lower permeabilities than their corresponding concretes. For example, the permeabilities of the regular and the high performance mortars are about

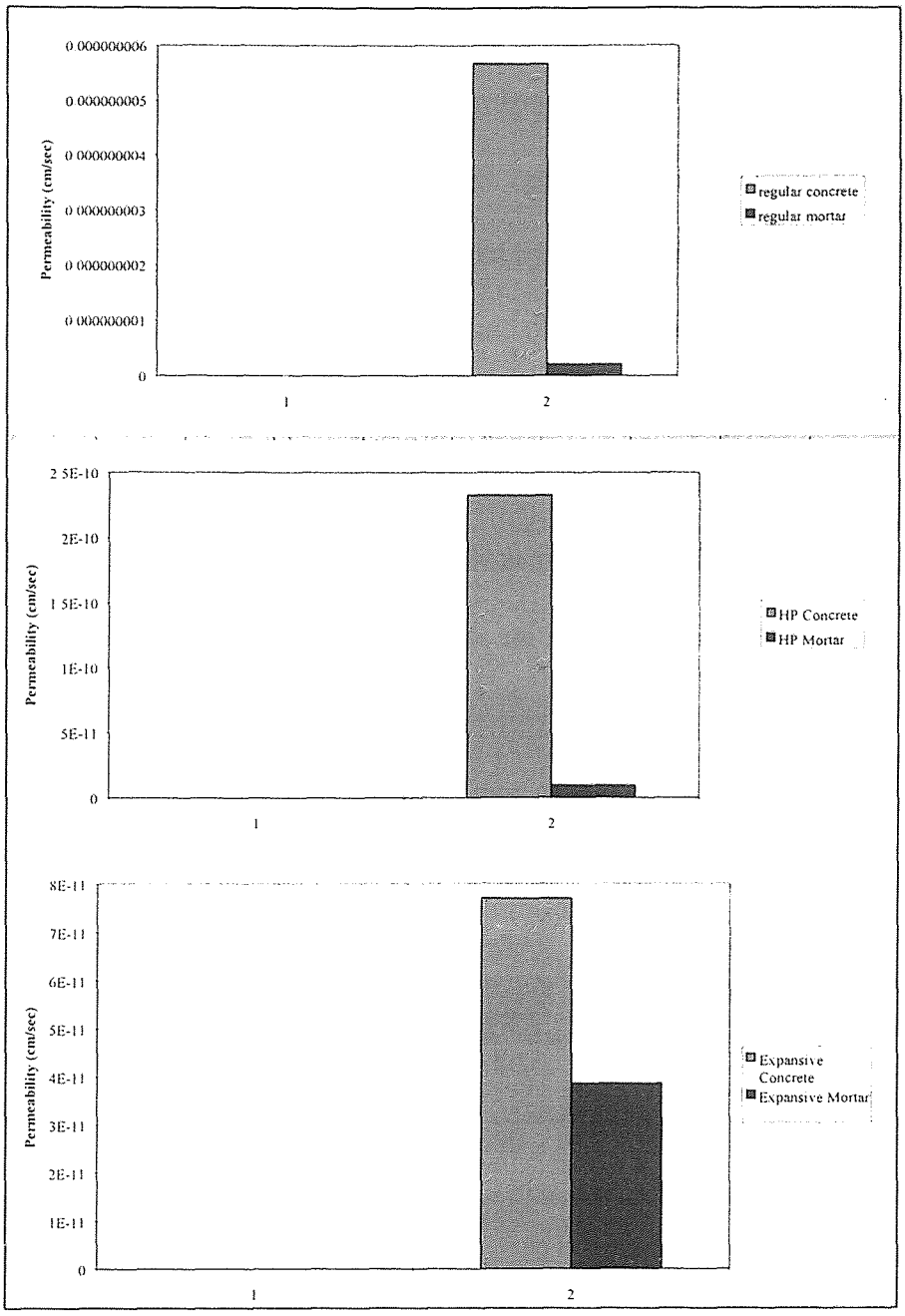

Figure 11. Comparisons of permeability of concrete and mortar

20 times smaller than that of the corresponding concretes. On the other hand, for the expansive concrete and mortar, the permeability of the mortar is just about 2 times

smaller than that of the concrete. It clearly indicates that the interfacial zones are the favorable pathways for water flow. The bone cracks in the interfacial zones are caused by the local stresses due to the thermal mismatch between the paste and the aggregate, or by the restraint of paste shrinkage by the aggregate. For the expansive concrete and mortar, some of the shrinkage are compensated by the material expansion so that the difference of permeabilities between the concrete and the mortar are not so significant.

3.4 Removal of the Chemical Species

The results of the concentration analysis by AA and HPLC for the chemical solutions in the inflow and the out flow containers are listed in Table 9. The percentage increase in

Table 9. Concentration and percentage change of the chemical species in inflow and outflow solution

Chemical Species	Stock Solution Concentration (mg/l)	Concentration in Inflow Container (mg/L)	% Concentration increase	Concentration in Outflow Container (mg/L)	% Removal
Pb^{2+}	1000	1180	18	354	65
Cr^{6+}	1000	1050	5	389	61
Dichlorofluorescein	1000	1457	46	53	95
Phenol	2000	2700	35	78	94

concentration or removal of each species in the solution is determined on the basis of the concentration of the species initially presented in the stock solution.

The results indicate that the concentration increase in the inflow container ranges from 5 to 18% for the heavy metal ions and 35 to 46% for the organic species. The greater concentration increase of the organic species reflects the size exclusion of the specimen to these larger molecules. The percentage removal of the species ranges from 61 to 65% for the heavy metal ions and 94.7 to 96.1% for the organics. These removals are most likely as a result of the adsorptions of these species on the interior matrices of the specimen.

CHAPTER 4

SUMMARY AND CONCLUSIONS

The results of the mechanical strength and the permeability of each specimen are summarized in Table 10.

Table 10. Summary of permeability and compression strength of the specimens

Specimen		Permeability (cm/sec)	Compression Strength (psi)
Regular	Concrete	5.7×10^{-9}	4200
	Mortar	4.5×10^{-10}	
High Performance	Concrete	2.3×10^{-10}	10600
	Mortar	1.0×10^{-11}	
Expansive	Concrete	7.7×10^{-11}	4200
	Mortar	5.0×10^{-11}	
Polymer Concrete	Blend	5.3×10^{-10}	3800
	Coated	5.0×10^{-11}	4200

The results indicate that among these samples investigated, the polymer coated regular concrete has the lowest permeability , 5×10^{-11} cm/sec, and the high performance

concrete has the highest compression strength, 10,600 psi, which is consistent with the reported value in the literature (Danqin Chen, Master Thesis, 1993).

Based on these findings, it is concluded that a high strength and low permeability concrete material, as required by the environmental container structure, could be achieved, simply by a surface treatment of the high performance concrete with a non-permeable polymer. To screen for such a polymer is thus recommended for the future study.

APPENDIX

CALCULATION OF HYDRAULIC DIFFERENCE

The hydraulic difference consists of two parts. One is the hydraulic head and the other is the pressure head. The hydraulic head is the difference of the height of the inflow and outflow. It can be read directly from the meter. The pressure head is the results of the pressure difference in inflow and outflow. It can be calculated as following.

The pressure can be described as:

$$P = \rho g h_p$$

here P is the pressure; ρ is the density of the mass, in our case, it is the density of water; g is the acceleration of gravity; h_p is the height. So the pressure head h can be calculate as:

$$h_p = P/\rho g$$

In my experiment, the pressure is read as *psi*. For the ρg, I use the specific weight of water at room temperature, which is 62.4 lb/ft^3. The h become:

$$h_p = P(lb/in^2)*[12(in/ft)]^3/62.4(lb/ft^3)$$

Here, the unit if h_p is inch. In the experiment, the hydraulic head was read as cm. So, for uniform the unit, I converted the inch to cm. The finial form of pressure head is as below.

$$h_p = P(lb/in^2)*[12(in/ft)]^3*2.54(cm/in)/62.4(lb/ft^3)$$

So, the hydraulic difference of inflow and outflow is as following.

$$h = H + \frac{P*12^3*2.54}{62.4}$$

The H is the hydraulic head.

REFERENCE

Barna, R., et al. "Solubility Model for the Pore Solution of Leached Concrete Containing Soilidified Waste." *Journal of Hazardous Materials*, Vol. 37 p 33-9, April 1994.

Bazant, Z., et al. "Effect of Cracking on Drying Permeability and Diffusivity of Concrete" *ACI Materials Journal*, Vol. 84, p 351-7, September/October 1987.

Chang, K., *Centrifugal Modeling Leaking Underground Storage Tanks*. Master Thesis, New Jersey Institute of Technology, 1991

Chen, D., *Stress-Strain Behavior of High Strength Concrete Cylinders*. Master Thesis, New Jersey Institute of Technology, 1995

Chuang, K., *The Permeability of Hot Mix Asphalt Concrete with Petroleu Contaminated Soils*. Master Thesis, New Jersey Institute of Technology, 1993.

Figg, J., "Concrete Surface Permeability: Measurement and Meaning." *Chemical and Industry*, Vol. 21, p 714-19, November 6, 1989.

Gagne, J., et al. "Effect of Supperplasticizer Dosage on Mechanical Properties, Permeability, and Freeze-Thaw Durability of High-Strength Concrete with and without Silica Fume." *ACI Material Journal*, Vol. 93, p111-20, March/April 1996.

Ludirdja. D., et al. "Simple Method for Measuring Water Permeability of Concrete." *ACI Material Journal*, Vol. 86, p 433-9, September/October 1989.

Mehta, P., "High-Performance Concrete Durability Affected by Many Factors." *Aberdeen's Concrete Construction*, Vol. 37, p 367-70, 1992

Naik, T., et al. "Permeability of High-Strength Concrete Containing Low Cement Factor." *Journal of Energy Engineering*, Vol. 122, p 21-39, April 1996.

Ozyildirim, C., et al. "Improved Concrete Quality with Combinations of Fly Ash and Silica Fume." *ACI Material Journal*, Vol 91, p 587-94, November/December 1994.

Rosenbaum, D., "Paris Inventor Touts Zero-Porosity Concrete (Z-90)." *ENR*, Vol. 225, p 18-19, August 9, 1990.

Sai, J., et al. "Barrier Wall Materials for Containment of Dense Nonaqueous Phase Liquid." *Hazardous Waste & Hazardous Materials*, Vol. 9, p 317-30, 1992.

David, W., et al. *Permeability of Concrete*, American Concrete Institute, 1987.

Zhang, M., et al. "Permeability of High-Strength Lightweight Concrete." ACI Material Journal, Vol. 88, p 463-9, September/October 1991.